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Preface

Dear Participants,

Confronted with the ever-increasing complexity of technical processes and the growing demands on their efficiency, security and flexibility, the scientific world needs to establish new methods of engineering design and new methods of systems operation. The factors likely to affect the design of the smart systems of the future will doubtless include the following:

- As computational costs decrease, it will be possible to apply more complex algorithms, even in real time. These algorithms will take into account system nonlinearities or provide online optimisation of the system's performance.
- New fields of application will be addressed. Interest is now being expressed, beyond that in "classical" technical systems and processes, in environmental systems or medical and bioengineering applications.
- The boundaries between software and hardware design are being eroded. New design methods will include co-design of software and hardware and even of sensor and actuator components.
- Automation will not only replace human operators but will assist, support and supervise humans so that their work is safe and even more effective.
- Networked systems or swarms will be crucial, requiring improvement of the communication within them and study of how their behaviour can be made globally consistent.
- The issues of security and safety, not only during the operation of systems but also in the course of their design, will continue to increase in importance.

The title "Computer Science meets Automation", borne by the 52nd International Scientific Colloquium (IWK) at the Technische Universität Ilmenau, Germany, expresses the desire of scientists and engineers to rise to these challenges, cooperating closely on innovative methods in the two disciplines of computer science and automation.

The IWK has a long tradition going back as far as 1953. In the years before 1989, a major function of the colloquium was to bring together scientists from both sides of the Iron Curtain. Naturally, bonds were also deepened between the countries from the East. Today, the objective of the colloquium is still to bring researchers together. They come from the eastern and western member states of the European Union, and, indeed, from all over the world. All who wish to share their ideas on the points where "Computer Science meets Automation" are addressed by this colloquium at the Technische Universität Ilmenau.

All the University's Faculties have joined forces to ensure that nothing is left out. Control engineering, information science, cybernetics, communication technology and systems engineering – for all of these and their applications (ranging from biological systems to heavy engineering), the issues are being covered.

Together with all the organizers I should like to thank you for your contributions to the conference, ensuring, as they do, a most interesting colloquium programme of an interdisciplinary nature.
I am looking forward to an inspiring colloquium. It promises to be a fine platform for you to present your research, to address new concepts and to meet colleagues in Ilmenau.

Professor Peter Scharff
Rector, TU Ilmenau

Professor Christoph Ament
Head of Organisation

Table of Contents

C O N T E N T S

7 New Methods and Technologies for Medicine and Biology

8 Embedded System Design and Application

10 Mobile Communications

11 Education in Computer Science and Automation

52nd Internationales Wissenschaftliches Kolloquium
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T. Bernard / H. Linke / O. Krol

A Concept for the long term Optimization of regional Water Supply Systems using a reduced Finite Element Groundwater Model

ABSTRACT

This paper presents an optimal control approach for the management of the surface and groundwater resources in a region with extreme water scarcity. For this purpose realistic models of the complete surface water system as well as a groundwater model of a large model area (6300 km^2) have been developed. The key point of the proposed approach is the reduction of the detailed 3D-Finite Element groundwater model to a linear state space model of sufficient low order (~20). In combination with the highly efficient numerical solution algorithm IPOPT the optimal control problem can be solved even for a long term horizon in a user-friendly response time. The results of two optimization scenarios demonstrate the performance of the implemented concept. Furthermore, it is shown that the approximation quality of the reduced linear model is very good.

1 Introduction

The very dynamic economic development in combination with a fast population growth has led to a huge water demand in the region of China's capital, Beijing. This region belongs to the semi-arid climate zone with a highly uneven distribution of the rain throughout the year. More than 80% of the annual precipitation is falling during the summer (July – September). The formerly abundant groundwater resources in the North China plain have been overexploited over the last decades resulting in a strong decline of the groundwater head (up to 40 m).

In a current research project a Decision Support System (DSS) for the management of the water resources in Beijing is being developed and implemented. The issues dealt with the DSS outlined in Figure 1 range from the optimization of reservoir extraction to the long-term strategic distribution of available water resources for industry, agricultural use and private households. For the design of the DSS a model of the entire water supply system of the Beijing region was developed. This complex model includes all essential elements to collect, store and distribute the surface and groundwater resources on a regional scale. Model based DSS for optimal water supply have been developed for more than twenty years [1], but many of them are dealing with very simplified models, especially for the groundwater system. In our approach the groundwater behavior has been modeled by spatially distributed 3D Finite Element model of the considered region. However, the optimization of the regional water resources management with respect to different assumptions for future exterior changes (e. g. economy, climate changes) is one key item of the DSS to be developed. The solution of optimal control problems based on a high-resolution groundwater model is time-consuming and would prevent the practical application of the DSS. Therefore the complexity of the 3D finite element groundwater model has to be drastically reduced. Hence in this paper a trajectory based scheme for groundwater model reduction is proposed.

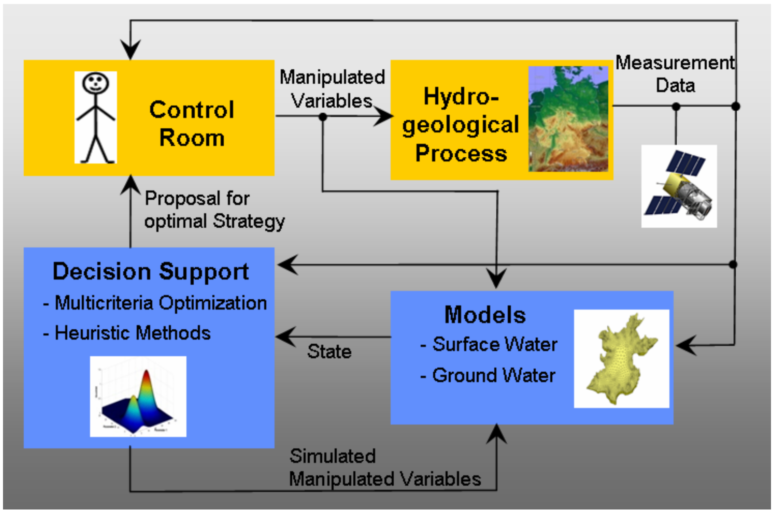

Figure 1: Basic Concept of the Monitoring and Decision Support System

This paper presents an overview of the developed process models for the surface water system (section 2) and groundwater resources (section 3) including model reduction. Aspects of the formulation and numerical solution of the optimal control problem are discussed in section 4. First results of the proposed optimal control approach for water management are presented in section 5.

2 Surface water model

Five reservoirs with a total storage capacity of roughly $9 \cdot 10^9$ m³ are important for the management of the natural surface water resources in the considered area and are therefore incorporated in the decision support system. The water is distributed to the customers using rivers and artificial transport ways (channels, pipes) of a total length of about 400 km. The water distribution system is formally described as a directed graph. The nodes represent reservoirs, lakes, points of water supply or water extraction and simple junction points. The water distribution process is described by the edges (e.g. river reaches, channels), whereas the flow dynamics is neglected according to the specified time step for decision support. The sole nonlinearity of the surface water model results from the volume-surface relation of the reservoirs, which is included to model the evaporation from the water surface and is described by a piecewise polynomial approach. Figure 2 shows the structure of the surface water system including the connections to the groundwater system.

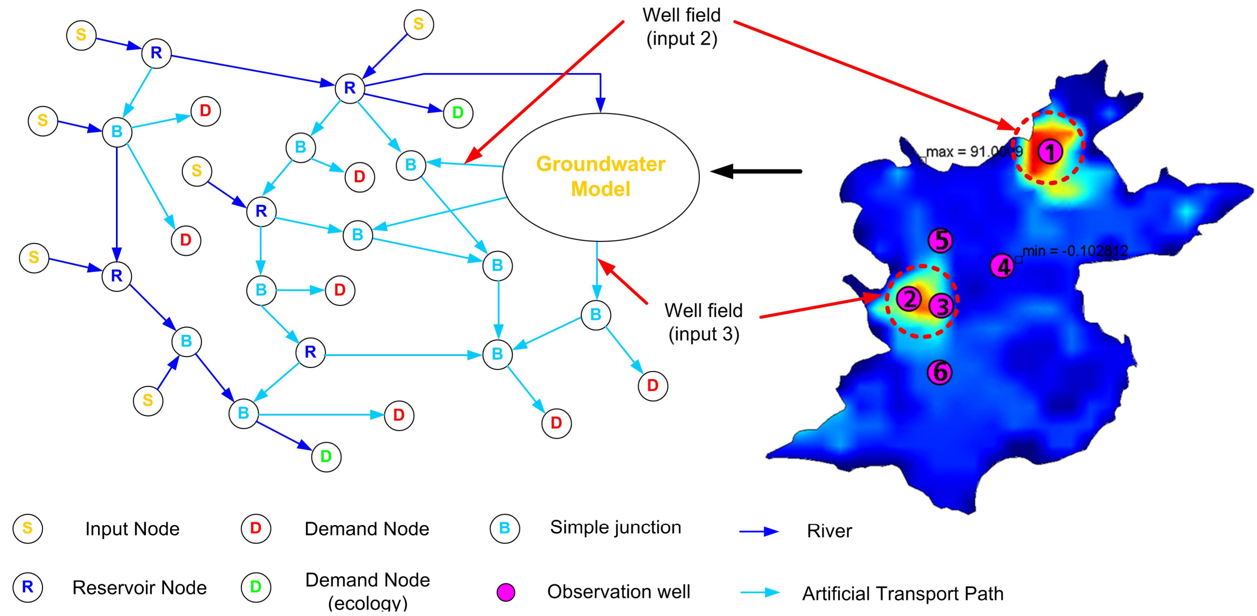

Figure 2: Structure and coupling of the reduced surface and groundwater model

3 Ground Water Model

3.1 Equations and Parameters of the 3D Finite Element Model

The second important water resource is the groundwater in the considered area that is modelled by a spatially distributed finite element groundwater model. The governing equation for groundwater flow is Darcy's law $k_f \cdot \operatorname{grad} h = \dot{q}$ [L/T] [2] describing slow streams through unconfined aquifers. It denotes *h* [L] the hydraulic head (which corresponds to the groundwater level) and $k_f\,(x,y,z)$ [L/T] is the hydraulic conductivity that governs the hydrogeological properties of the soil. Combining Darcy's law with mass conservation one yields the partial differential equation (1) which is a diffusion equation.

$$S_0 \frac{\partial h}{\partial t} - \operatorname{div}\left(k_f \cdot \operatorname{grad} h\right) = Q \qquad (1)$$

(1) is an initial-boundary value problem which has to be solved for *h* in the 3 dimensional model domain Ω. The initial condition is $h(\Omega,t_0)$ (groundwater surface) at the initial time

t_0 in Ω. Boundary conditions are chosen of Dirichlet type, i.e. $h(\partial\Omega)$ at the boundary $\partial\Omega$ which are assumed to be time-independent. In (1) $S_0(\Omega)$ [1/L] denotes the specific storage coefficient. $Q(\Omega,t)$ [1/T] summarizes all sources and sinks that coincide with the groundwater recharge and the exploitation in Ω. The main task with respect to the groundwater model is the parameterization of the large-scaled model covering an area of 6300 km². On the one hand the time independent parameters k_f, S and boundary condition $h(\partial\Omega)$ have to be estimated and generalized for the whole domain Ω by a set of measured values. On the other hand the source / sink term $Q(\Omega,t)$ has to be calculated time-dependent. Q can be divided in the source term $Q_{expl}(\Omega,t)$ which describes the groundwater exploitation rates due to industry, households and agriculture and the groundwater recharge $Q_{rech}(\Omega,t)$ as a sink which corresponds to the flow into the groundwater storage e. g. due to precipitation. It holds

$$Q = Q_{rech} - Q_{expl} \tag{2}$$

The calculation of Q_{rech} and Q_{expl} (especially exploitation by agriculture) is performed by means of a geographical information system (GIS) that is appropriate to compute spatially distributed data. For these calculations only a spatial distributed precipitation and water demand is needed (these data are in general available). The water demand is split into the three user groups households, industry and agriculture, whereby a part of the agricultural water demand is covered by precipitation. The rest of the agricultural demand has to be fulfilled by irrigation, whereby a part of it is covered by waste water.

3.2 Reduction of the Ground Water Model

For the optimization of the water allocation system the full 3D Finite Element model is not very suited due to the large computational time. As for optimization a prediction of the hydraulic head (groundwater level) at a set of representative points is sufficient an input-output model (e.g. a linear state space model) with considerably smaller order $n < 50$ than the original FEM model has to be derived. The sources and sinks of the groundwater system are regarded as input of the model as the water allocation and irrigation has to be optimized. The spatially distributed allocation of water is realized by a withdrawal for agriculture, which covers the whole model area (input 1) and two well fields (input 2 and 3, see Figure 2) which cover only a small fraction of the model area. Finally, the irrigation is also considered as input 4 of the reduced groundwater model. By a trajectory and identification based approach the original 3D-Finite Element model with ~100.000 nodes has been reduced to a state space model with only 18 states. The reduced model has only a small approximation error (cf. results in section 5). For details regarding the model reduction see [3].

4 Setup and solution of the optimization problem

The water management problem is stated as discrete time optimal control problem:

$$\min_{\boldsymbol{u}^k, k=1,\ldots,N} \left\{ F\left(\boldsymbol{x}^N\right) + \sum_{k=0}^{N-1} \boldsymbol{f}_0^k\left(\boldsymbol{x}^k, \boldsymbol{u}^k, \boldsymbol{z}^k\right) \right\} \tag{3}$$

subject to

$$\mathbf{x}^0 = \mathbf{x}(t_0), \quad \mathbf{x}^{k+1} = \mathbf{f}^k\left(\mathbf{x}^k, \mathbf{u}^k, \mathbf{z}^k\right), \quad \mathbf{h}^k\left(\mathbf{x}^k, \mathbf{u}^k, \mathbf{z}^k\right) = \mathbf{0}, \quad \mathbf{g}^k\left(\mathbf{x}^k, \mathbf{u}^k, \mathbf{z}^k\right) \leq \mathbf{0} \qquad \text{(4a,b,c,d)}$$

where it denotes: $\boldsymbol{x}$: state variables, $\boldsymbol{u}$: control variables, $\boldsymbol{z}$: uncontrollable inputs (e.g. inflow to the reservoirs, evaporation), N: optimization horizon in time steps. The process equations (4b) contain the balance equations of the reservoir nodes and the reduced groundwater model. The balance equations of non-storage nodes are formulated as general equality constraints (4c) and technical capabilities of the water supply system (e.g. maximum capacity of channels or pipes) are described by inequality constraints (4d). The goals of the water management are transformed into the objective function (3) (which evaluates e. g. demand fulfillment or sustainability) and inequality constraints (e.g. time varying maximum storage volume of reservoirs, minimum rate of demand fulfillment, minimum groundwater head). The initial state $\boldsymbol{x}^0$ and predictions for the non-controllable inputs $\boldsymbol{z}$ over the full optimization horizon N are a prerequisite to solve the optimal control problem.

The discrete time optimal control problem (3) - (4) is numerically solved as a large-scale nonlinear programming problem in the state and control variables. Due to the high dimension of this solution approach for the discrete-time optimal control problem, it is essential to take the special sparsity structure of the problem into account. The optimization solver *IPOPT* is used as core numerical routine [4]. The problem interface for multistage optimal control problems of the optimization solver *Hqp* [5], which provides an efficient way for the problem formulation, is linked to *IPOPT*. The nonlinear programming problem resulting from a time horizon of 5 years with a sample time of 5 days has about 23,000 optimization variables and is solved in approximately 120 steps requiring about one 15 min time (Pentium 2.8 GHz).

5 First Results with the Optimal Control Approach

The performance of the proposed optimal water management concept is demonstrated by means of two optimization scenarios. In <u>scenario A</u> it is assumed that no constraints with respect to the groundwater observation points $\{h_i\}$, $i=1,\ldots,6$ are defined, while in scenario B a time dependent lower limit (constraint) to the hydraulic head of observation point 5 is applied as it is shown in Figure 4 on the upper subplot on the right side. In both cases the objective function contains terms to reduce the difference between water demand and supplied water as much as possible (i. e. fulfill demand to highest possible degree). The optimization horizon is $t_h = 5$ *years.*

In Figure 3 results of the surface water system are presented. On the left the time plot of the water level of one exemplary reservoir is shown. It can be seen that for scenario B the water of the reservoir is used during $t = 0 \ldots 1.5$ *years* for groundwater recharge fields in order to fulfill the applied groundwater constraint. Note that in this management strategy the lower bound for the reservoir water level is reached for several times (at $t = \{1.5, 2.5, 3.5, 4.5\}$ *years,* cf. Figure 3), whereas in scenario A the water level of the reservoir is only slightly decreased. On the right of Figure 3 the time plot of the global surface water supply is shown. It is obvious that the water demand of the different customers is fully supplied in scenario A, while in scenario B the required increase of the groundwater head at point 5 yields a demand deficit of about 25 %.

Figure 4 shows on the upper left side the time plot of ground water extraction from the well field 2 and on the lower left side the artificial groundwater recharge. In the middle of Figure 4 the hydraulic head h at the observation points 5 and 6 (= output 5, 6) can be seen. In the right of Figure 4 the approximation error Δh of the reduced model (i.e. difference of output of full FEM model and reduced state space model) is shown. Obviously Δh of output 6 ($|\Delta h_{max}| \sim 0.1$ m) is smaller than for output 5 ($|\Delta h_{max}| \sim 0.35$ m), but both errors are small compared to the changes of these outputs which means that the approximation quality of the reduced model is good.

In scenario B the allocation of the well field, which is not located close to the point 5 and hence has only a little impact to this point, is increased to its upper limit. For the groundwater recharge (irrigation) the result of scenario A is a nearly constant value over time while in scenario B an interesting decrease at $t = 0 \ldots 1.5$ *years* can be observed. This decrease of groundwater recharge corresponds to the increased allocation from the reservoir which has been discussed. So obviously the optimization changes the management strategy in a transparent way. It is also obvious that the applied constraint of scenario B at point 5 is not violated, i.e. the hydraulic head is increased by the optimal control.

Summarizing, it can be stated that the water management system works in a transparent and user-friendly way as it is easy to parameterize with time-dependent constraints on the hydraulic head at certain locations. The optimal control concept is planned to be launched as a component of a Decision Support System in a first version during the Olympic Games 2008 in Beijing.

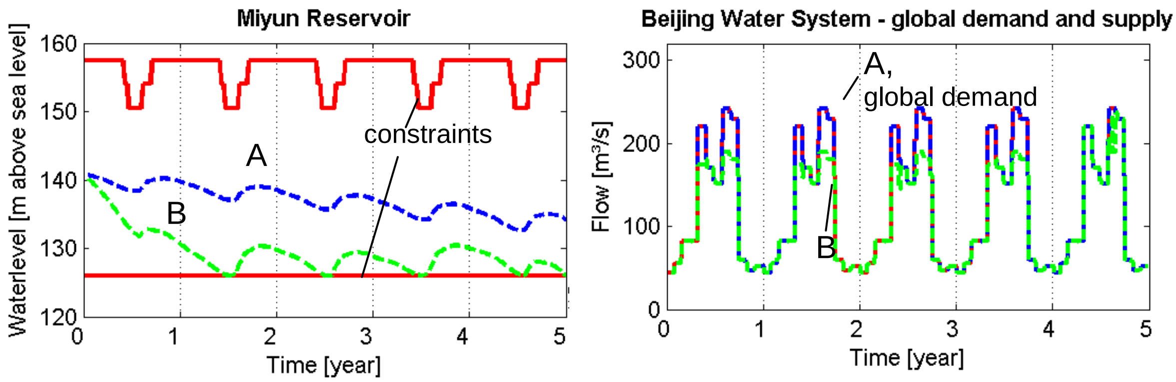

Figure 3: Results of the surface water system of scenarios A and B.

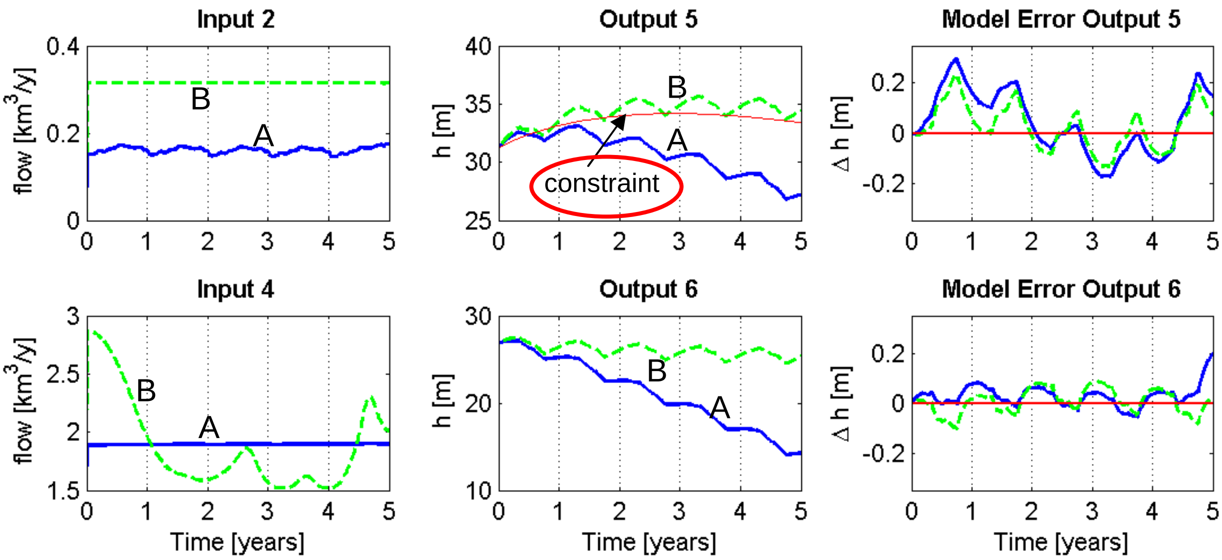

Figure 4: Results of the groundwater system of scenarios A (solid —) and B (dashed ·····)

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